Correction of the Temperature Dependent Error in a Correlation Based Time-of-Flight System by Measuring the Distortion of the Correlation Signal

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ABSTRACT

Correlation based time-of-flight systems suffer from a temperature dependent distance measurement error induced by the illumination source of the system. A change of the temperature of the illumination source, results in the change of the bandwidth of the used light emitters, which are light emitting diodes (LEDs) most of the time. For typical illumination sources this can result in a drift of the measured distance in the range of \textasciitilde 20 cm, especially during the heat up phase. Due to the change of the bandwidth of the LEDs the shape of the output signal changes as well. In this paper we propose a method to correct this temperature dependent error by investigating this change of the shape of the output signal. Our measurements show, that the presented approach is capable of correcting the temperature dependent error in a large range of operation without the need for additional hardware.

Keywords: 3D camera, time of flight, temperature dependent error, correction method

1. INTRODUCTION

The number of applications using 3D cameras has steadily increased in recent years. One possible implementation that proved to be highly immune to background light (BGL) is a correlation based time-of-flight (TOF) system\textsuperscript{1}. However, these cameras show a temperature dependent error induced by the illumination source. Most of these illumination sources consist of an array of LEDs. Their bandwidth and also their rise and fall times are strongly influenced by their operating temperature. This bandwidth variation results in a temperature dependent error, being particularly a problem during the heat up phase. For typical light sources the measured distance can drift in the range of \textasciitilde 20 cm.

One solution to eliminate the described error is to measure the length of a known reference path during operation\textsuperscript{2,5}. This method works sufficiently well in a large operating range. However, it requires additional hardware and therefore causes additional costs. In\textsuperscript{2} several correction methods were investigated for a previous generation of our distance measurement sensors. In this work we present an approach to correct this temperature dependent error which does not need any additional hardware for the sensor presented in\textsuperscript{1}.

2. TIME OF FLIGHT MEASUREMENT PRINCIPLE

In TOF measurement systems the time is measured that it takes the light to travel from the light source to an object in the scene and back to the camera. Due to the constant speed of light \( c_0 \) the distance \( d \) of the object can be derived out of the runtime of light signal \( t_{\text{TOF}} \) by

\[ d = \frac{t_{\text{TOF}} \cdot c_0}{2}. \tag{1} \]

Due to the fast speed of light the measurement of the light propagation time is challenging. In correlation based TOF systems this runtime measurement is done by using a modulated light signal and measuring the phase difference between the transmitted and the received signal. Fig. 1 illustrates the functional principle of correlation based TOF systems.
light source emits a modulated optical signal of rectangular shape. Backscattered light from the scene is then correlated with a reference clock on chip. The phase shift between the backscattered light and the reference clock is directly proportional to the distance of the object. Due to the rectangular shapes of the correlated signals this correlation operation results in a triangular-shaped waveform. The phase of this triangle corresponds to the phase $\Delta\varphi$ between backscattered light and the reference clock. Therefore, it is proportional to the distance of the object. The distance $d$ can be therefore derived by

$$d = \frac{c_0}{4\pi f_m} \Delta\varphi,$$

where $c_0$ is the speed of light and $f_m$ is the modulation frequency of the light signal. For the presented measurements a modulation frequency of $f_m = 12.5\ \text{MHz}$ was used. During the correlation operation the correlation triangle is sampled in $N$ discrete phase steps. For the investigated 3D sensor typically $N=16$ phase steps are used.

Due to the periodicity of the optical signal, the unambiguity range of this measurement system is limited by

$$d_{\text{max}} = \frac{c_0}{2 f_m},$$

resulting in a measurement range of $\sim 12\ \text{m}$ for $f_m=12.5\ \text{MHz}$. If a larger measurement range is required, this can be achieved by decreasing the modulation frequency or by measuring twice with slightly different modulation frequencies.

During the correlation operation, the product of the received signal and the reference clock is integrated for each phase step for the integration time $T_{\text{int}}$. For the presented measurements the integration time for each phase step was set to the relatively short time of $20\ \mu\text{s}$ in order to guarantee a large dynamic range. Each correlation triangle was sampled with $N=32$ phase steps. For each measurement point an internal averaging over 128 triangles was applied.

3. TEMPERATURE DEPENDENT ERROR

The temperature dependent error arises mainly due to a change of the shape of the optical signal that is emitted by a LED light source. When the shape of the received light signals changes, the corresponding correlation triangle will accordingly alter its shape as well. Fig. 2 shows a simulation of correlation triangles for light signals with different rise and fall times. The light signal was modeled as a rectangular signal that is filtered by a $1^{\text{st}}$ order low-pass with a cutoff frequency $f_{\text{cutoff}}$. It is clearly visible that increasing rise and fall times results in shifting the correlation triangle and subsequently in shifting the measured distance. Additionally to the phase shift the shape of the triangle changes so that for increasing rise and fall times the triangle becomes smoother.

In our approach we make use of this fact to correct the temperature dependent phase shift. The smoother the triangle is, the smaller is the amplitude of the harmonics relative to the amplitude of the fundamental wave. Since the amplitude of
these harmonics can be measured during runtime, they can be used to correct the temperature dependent error. For this correction method the second harmonic is used, being the largest one. Only the even harmonics exist due to the symmetry of the triangle. In order to get independent of the amplitude of the triangle, the second harmonic relative to the fundamental wave is used instead of the absolute value.

4. MEASUREMENT SETUP

In Fig. 3 the measurement setup is illustrated. The FPGA generates both, the modulation signal for the illumination source and the reference clock, as well as all necessary control signals required by the 3D sensor. The used FPGA was a Stratix IV FPGA from Altera on a Terasic DE4 board including an additional retiming and readout board. A detailed description of this signal generation and readout board can be found in a.

The electrical modulation signal is passed through an arbitrary waveform generator to generate a low-pass filtered signal with adjustable cutoff frequency out of the rectangular signal. This electrical signal is then transformed into an optical one using a 635 nm single-mode laser source. The combination of the arbitrary waveform generator and the laser source allows emulating the temperature dependence of the LEDs in a very systematic and reproducible way. The typical change of the LED bandwidth due to a temperature change amounts to several MHz. The investigated bandwidth range from $f_{3dB} = 5$ MHz to $f_{3dB} = 100$ MHz is considerably larger than this and covers the typical bandwidths of high power LEDs and small LEDs that are considered as being faster.

The output power of this laser source is adjustable over more than 40 dB, allowing investigating the dynamic range of the sensor and the correction method. The light is then guided via a single mode fiber directly to the pixel of the 3D camera chip. The usage of the single-mode fiber guarantees that the whole light is fed into the photodiode of the pixel.

A personal computer is used to control the whole measurement setup. This allows automatically stepping through the different values for the electrical bandwidth of the optical signal and the received optical power at the pixel. Furthermore the control computer receives the correlation triangles from the FPGA and allows postprocessing and storage of the measurement data.
In Fig. 4 the bandwidth dependent error $d_{err}$ against the received optical power $P_{opt}$ and the cutoff frequency of the illumination source is plotted. A strong dependence of this error on the cutoff frequency is visible. In the total investigated frequency range from 5 MHz to 100 MHz the distance measurement error changes by more than 2 m. It is important to mention here, that for typical LEDs the change of the bandwidth will not be in this large range but in the range of some MHz, resulting in a drift of ~20 cm. The error is almost independent of the received optical power $P_{opt}$. 
Figure 5. Measured relation between cutoff frequency and measurement error (a), cutoff frequency and the relative amplitude of the second harmonic of the correlation triangle (b) and the resulting correction curves (c).

Figure 6. Relation between the received optical power and the amplitude of the fundamental wave $A_0$ of the correlation triangle.

**CORRECTION METHOD**

Fig 5 (a) shows the measured relation between the cutoff frequency $f_{3dB}$ of the rectangular light signal and the temperature dependent error $d_{err}$. In Fig 5 (b) the relation between $f_{3dB}$ and the relative amplitude of the 2nd harmonic $A_{2,rel}$ of the triangle is shown. Some of the correction curves for different received optical powers $P_{opt}$ are are plotted in.
Fig. 5(c). They can be obtained by combining the results from Fig 5 (a) and (b). A small dependence of this relation on the received optical power can be seen. However, this problem can be suppressed since the amplitude of the fundamental wave $A_0$ of the triangle is directly proportional to the received optical power over a wide range as can be seen in Fig. 6. The deviation of this relation from the linear characteristic for large received optical power can be explained by saturation of the correlation circuit in the pixel. This effect can be reduced by decreasing the integration time $T_{int}$.

The amplitude of the fundamental wave can be used to choose the corresponding correction curve. In a practical implementation the correction curves are stored in a two-dimensional lookup table in the control logic. The correction values for points between the nodes of the lookup table can be obtained by two-dimensional interpolations. The lookup table can be obtained by using the measurement setup depicted in Fig. 3. In the real application the approximation of the first order low-pass filtered signal for the light signal has to be replaced by the real behavior of the used LEDs.

The limited number of phase steps $N$ results in a systematic phase dependent error caused by undersampling of the triangular shape. In Fig. 7 it is shown, that for $N \geq 16$ this phase dependent error can be neglected for the standard measurement. Nevertheless the relative second harmonic $A_{2\text{rel}}$ of the correlation triangle depends slightly on the actual phase as shown in Fig. 8. Maximum error caused by the limited number of phase steps during correction.
in the MATLAB simulation results plotted in Fig. 7. For this simulation an ideal correlator and an ideal rectangular shaped received optical signal were assumed. The measured values for $A_{opt}$ in Fig. 5 are smaller than the simulated ones since the real correlator has a limited bandwidth. If $A_{opt}$ varies too much for different phases, it has to be considered during the correction process, resulting in increased complexity. MATLAB simulation results plotted in Fig. 8 show that for $N=16$ the undersampling of the correlation triangle produces a systematic error $\delta_{err,max}$ up to $-10$ cm during the correction operation. For $N \geq 32$ this undesirable effect causes an error smaller than 1 cm in the whole investigated frequency range. In the frequency range around some few tens of MHz, which is the main frequency range of high power LEDs, the error is even smaller and can be expected in the range of $\sim 2$ mm. Therefore, this error can be neglected for $N \geq 32$. For the presented measurement results $N=32$ phase steps have been used. If $N=16$ phase steps are used, the two dimensional lookup table has to be extended to a three-dimensional one, by including the phase information.

5. MEASUREMENT RESULTS

A comparison measurement that at best illustrates the influence of the presented approach is presented in Fig. 9. In contrast to the original measurement plotted in Fig. 4, the corrected version $d_{corr}$, plotted in Fig. 9, shows a strongly reduced bandwidth dependent error in a wide range of operation without requirements for additional hardware. The presented approach will therefore considerably lessen the temperature dependent error.

The increased error for very large received optical power results from saturation of the correlator in the pixel. This effect can be reduced by further reducing the integration time $T_{int}$.

As can be seen, due to the small signal-to-noise ratio for very weak optical signals, the error is increased again. In this case, the error can be reduced by increasing the SNR through extending the integration time $T_{int}$ and/or by averaging over more triangles.
6. CONCLUSION

A correction method for the temperature dependent error of a correlation based TOF 3D camera induced by the illumination source of the system was investigated. It could be shown, that the proposed approach is able to correct this error in a very broad range. Compared to the method using a reference path investigated in\textsuperscript{\textapo}, the proposed method has an increased calibration demand. However, in contrast to the method using the reference path it does not need any additional hardware, resulting in lower cost and simpler camera design.

REFERENCES